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USAAVRADCOM-TR-82-D-37

COMBAT MAINTENANCE CONCEPTS AND REPAIR TECHNIQUES USING SHAPE MEMORY ALLOYS FOR FLUID LINES, CONTROL TUBES, AND DRIVE SHAFTS

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Prepared for

APPLIED TECHNOLOGY LABORATORY
U. S. ARMY RESEARCH AND TECHNOLOGY LABORATORIES (AVRADCOM)
Fort Eustis, Va. 23604

APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

The results of this effort determined the feasibility of using the full-ring shape memory alloy (SMA) coupling to repair fluid lines, control tubes, and small diameter drive shafts. The flexible tube coupling, C-coupling, and interlocking coupling experienced problems with their installation or manufacture and are not considered to be viable repair concepts. Additional design effort would be required to solve these problems.

Testing of the SMA repair couplings has been conducted under an in-house test program. Upon successful completion of an appropriate environmental test program, it is planned to include the SMA repair couplings in battle damage repair kits for fluid lines and control tubes.

Mr. John Ariano, Aeronautical Systems Division, served as technical monitor for this contract.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

This report describes the design and testing of couplings fabricated from shape-memory brass (Betalloy) and used for the repair of helicopter battle-damaged hydraulic lines (rigid and flexible), control tubes, and drive shafts. Flameless heaters were investigated for fueled aircraft. Hydraulic rigid couplings generally exceeded the strength of the tubing. Flexible couplings were sensitive to installation. C-type couplings for nonsevered damaged tubing added to the strength significantly but were difficult to fabricate large enough to fit over the tubing without cutting the tube.

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SUMMARY

Shape memory couplings have been investigated for helicopter battlefield repair of damaged hydraulic lines (both rigid and flexible), control tubes and rods, and tail rotor drive shafts. Thirteen different types of parts (eleven distinct and different designs) were fabricated. Nearly 150 pieces were formally tested in tensile, torsional, temperature, and fatigue modes. Air and hydraulic leak, burst, and impulse tests were made to the limits of the parts or the tubing to which they were connected. An equal number of engineering parts were fabricated and tested during preliminary design evaluation. In general, full circular couplings exceeded the strength of the tubing they were repairing and assembly was straightforward with little skill required. C-type couplings performed adequately but could not be expanded sufficiently wide to permit installation on an unsevered tube. Flexible couplings performed well in hydraulic testing but were prone to leaking when tested with air only. Assembly of flexible couplings was also skill-sensitive and inclined to be dependent upon the tubing tolerance. Catalytic heaters were designed and fabricated for installation of parts in a flameless environment. Special interlocking couplings for repairing unsevered control rods were built and tested.

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INTRODUCTION

Considerable effort has been expended in determining vulnerability characteristics of Army helicopters; an even greater effort has been directed toward decreasing vulnerability of these systems. It is obvious, however, that although substantial improvements in survivability can be achieved, there will be a need for extensive repair when a helicopter has been subjected to combat damage. Most survivability analyses examine the probability of continued operation following damage for a designated period of time (30 minutes, for example). Such a capability is designed to provide adequate protection for safe return to a friendly site; when this occurs, the helicopter is considered "saved." A total operational analysis for midintensity combat will show, however, that if the damaged helicopter cannot be returned to a serviceable condition within a very short period of time (eight hours, for example), the helicopter will most likely be lost. This occurs due to mobility requirements of the modern battlefield and the unacceptable logistics problems associated with moving nonoperational helicopters.

Recognition of the problem has led to an increased concern and emphasis on combat damage repair for Army helicopters. The Applied Technology Laboratory has initiated a program entitled "Combat Maintenance for Army Helicopters." The proposed effort, as part of the overall program, presents one approach for accomplishing a wide range of combat damage repairs with the use of shape memory alloys (SMAs). SMAs are a class of metal alloys that can accept deformation below transition temperature range. Upon heating the alloy past its transition temperature range, this deformation is recovered and the part returns to its initial shape. A variety of SMA products are available and currently being used in hydraulic and electrical systems of both military and commercial aircraft. The key to their consideration for helicopter repair is the speed of installation, simple construction, strength, and generic simplicity of installation and application. The objective of this program is to evaluate existing designs of the SMAs for helicopter maintenance applications.

Specific repair problems pertinent to this program are associated with:

- Rigid fluid lines
- Flexible fluid lines
- Control (push-pull) tubes
- Tail rotor drive shafts

It is expected that shape memory alloys can be used for making repair components for these items. The strength of shape memory alloys used in existing tube and pipe couplings makes them ideal for the rigorous task of repairing high pressure tubing and aircraft control rods and shafts. Their speed and ease of installation suggests their suitability for mobile depot repair and even "on-the-spot" battlefield repairs.

SHAPE MEMORY ALLOYS

DESCRIPTION

A number of alloys, including steels, go through a reversible change in crystal structure as their temperature changes. The low temperature phase, martensite, with its distinct crystal structure, often has mechanical and physical properties quite different from those of the high temperature phase, austenite. Further, if the martensite of a particular alloy has a highly twinned structure, a phenomenon known as shape memory is possible. Raychem has explored this type of alloy and has developed two types that have the most commercial promise: Tinel™, a nickel-titanium alloy, and Betalloy™, a copper-based alloy.

Alloys exhibit shape memory as demonstrated in Figure 1. The relatively rigid austenitic structure is transformed to the highly twinned martensite as the alloy is cooled through its martensitic transformation temperature. This martensitic structure can be deformed easily by applying stress which causes twin boundaries to migrate to a preferred orientation. This deformation is reversed by heating the material through its austenitic transformation temperature, causing the structure to realign. Normally imperceptible motions that occur in individual atoms when the material is cycled through its transformation temperatures can become significant and useful when the individual motions become additive through selective orientation of the twins.

Transformation temperatures occur over a wide range by varying constituent concentration. The martensitic start transformation temperature is lower than the austenitic start reversion temperature due to hysteresis in the material. Both can be changed but, in general, there is a fixed difference between these two temperatures for each given alloy. Figures 2a and 2b illustrate alloys with transition temperatures above and below ambient, respectively. Figure 2a shows an alloy that is austenitic (Type

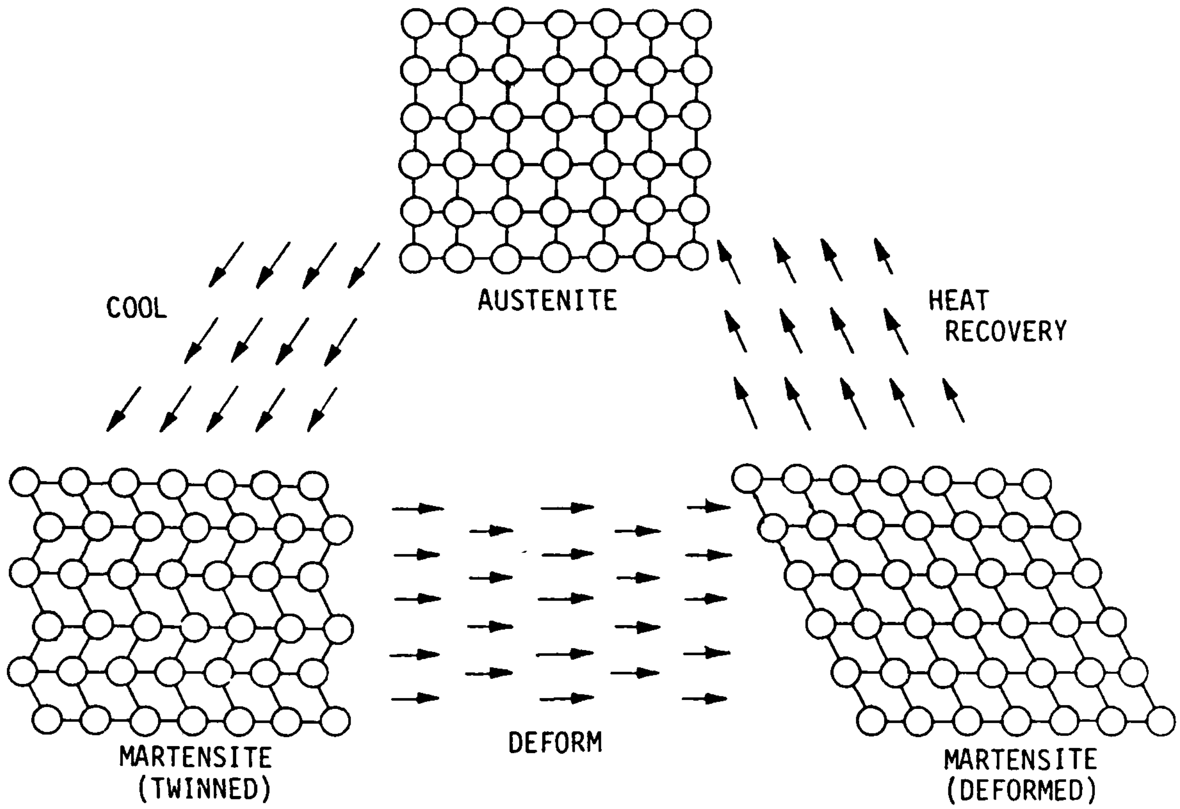


Figure 1. Shape memory representation.

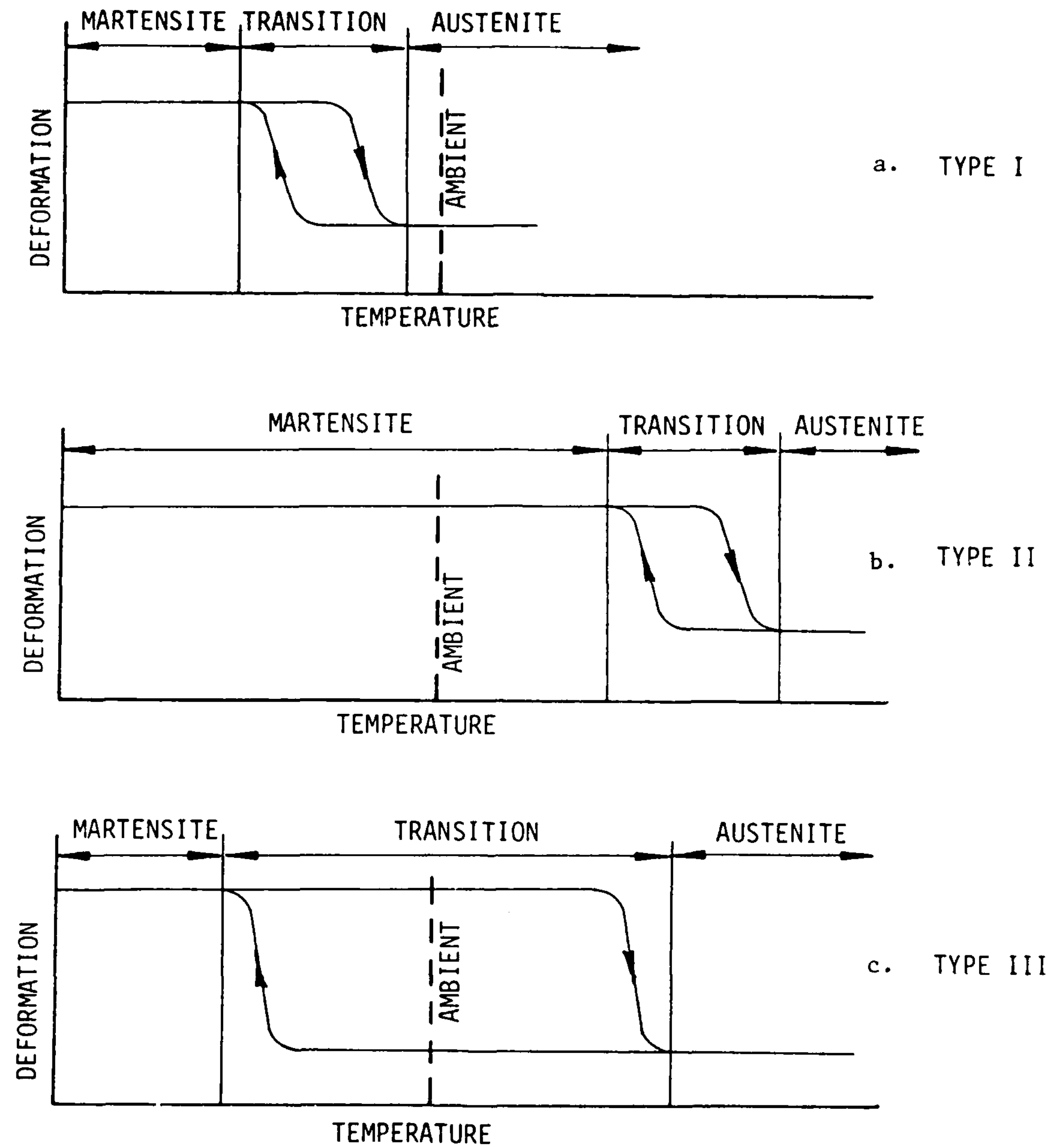


Figure 2. Illustration of shape memory alloy types and transformation temperatures.

I) at room temperature. Deformed parts, in this case, must be refrigerated to prevent recovery until ready for use.

Figure 2b shows an alloy (Type II) which is martensitic at ambient. Cold storage is unnecessary in this case. The part will not recover until it is raised above ambient to the austenitic transformation temperature. At ambient, however, the alloy is in the weaker martensitic phase.

Figure 2c indicates an alloy (Type III) with advantages of both Type I and II. Ambient temperature is in the wider transformation region. The part will only recover when heated above ambient and transformed to austenite. It will remain in the stronger austenitic phase on cooling to ambient because it is above the martensitic transformation temperature.

Nickel-titanium alloys with shape-memory performance were discovered at the Naval Ordnance Laboratory. Development work at Raychem led to modifications and improvements that have resulted in a number of specific alloys with desirable properties. These alloys are called Tinel and are available in both Type I and Type II (see Figure 2). Most applications have been with the Type I, a high-performance alloy used in both military and commercial applications. The mechanical properties and superior corrosion resistance of Tinel are responsible for the excellent performance of Cyrofit pipe and tube couplings.

Copper-based alloys can also exhibit shape memory. These alloys (called Betalloy) were developed at Raychem and are available as Type I, Type II and Type III. Type III is the most versatile and commonly used. Although Betalloy is less robust than Tinel, its economies and installation advantages often make it the better choice for many applications.

Properties of these alloys are listed in Table 1. Tinel has more memory, is stronger at room temperature, and has a wider operating temperature range (although this will not be as significant in short-term

applications). Betalloy alone has a Type III alloy--one that is austenitic during use but does not require cryogenic shipping and storage. It is also much easier to work. Complicated designs are more practical. For these latter reasons, Betalloy was used exclusively in this program.

Table 2 lists components fabricated and tested along with operational and test requirements for each. Table 3 lists material characteristics of specific tubing used for qualification. Components, in general, are modifications of existing coupling designs. Tubing, in many cases, was salvaged from damaged aircraft to represent realistic evaluation. Flameless catalytic heaters were fabricated for representative examples of couplings. Table 4 lists each item that was fabricated and tested with its drawing number. Assembly drawings of each item are shown in Figures 3-9.

Table 1. ALLOY PROPERTIES

	Units	TINEL Type I	TINEL Type II	BETALLOY Type I	BETALLOY Type II	BETALLOY Type III
MECHANICAL						
Young's Modulus	psi x 10^6	12	5	10	10	10
Ultimate Strength	psi x 10^3	115	140	100	100	100
Yield Strength (@ 20°C)	psi x 10^3	60	11	45	20	45
Elongation at Failure	%	12	15	8	8	8
SHAPE MEMORY						
Austenitic Transformation Temperature at Installation	°C	-130	20	-30	40	50
Martensitic Transformation Temperature on Cooling	°C	-160	28	-40	30	-40
Shape Memory	%	8	8	4	4	4
PHYSICAL						
Density	g/cm^3	6.4	6.4	7.6	7.6	7.6
Coefficient of Thermal Expansion (@20°C)	°C x 10^{-6}	5.8	5.8	18	18	18
Thermal Conductivity	Watt/cm°K	0.2	0.2	1.2	1.2	1.2
Specific Heat	cal/gram°C	0.1	0.1	0.094	0.094	0.094
Long-Term (10 Yrs) Operating Temperature Range	°C	-75 to 300	-28 to 300	-30 to 125	50 to 125	-30 to 125

Table 2. HELICOPTER COMPONENTS FOR REPAIR CONSIDERATION

COMPONENT	GENERAL DESCRIPTION	OPERATIONAL REQUIREMENTS	TEST REQUIREMENTS	MIN. NO. OF SMA TEST SAMPLES TO BE TESTED
Rigid Fluid Lines	0.125 to 2.0 inch O.D. in 0.125-inch increments. Steel and aluminum.	3000 psi steady and impulse for steel; 1500 psi impulse for aluminum.	Two times operational requirement	10 samples: 2 sizes fluid lines, 5 samples each size.
Flexible Fluid Lines	MIL-H-27267	1500 psi steady and impulse	Two times operational requirement	10 test samples: 2 sizes control tubes, 5 samples each size
Control Tubes (Push-pull tubes)	0.375 to 1.500 inch O.D. in 0.125-inch increments. Wall thickness = 0.028, 0.035 and 0.049 inch. 2024-T3 aluminum alloy.	Compression and tension loading of 2000 lb for application on unsevered line.	Two times operational requirement	20 test samples: 2 sizes control tubes, 2 types of repair (full-ring and C), 5 samples of each combination.
Tail Rotor Drive Shaft	1.00-inch O.D., 0.050-inch wall thickness. 2024-T3 aluminum alloy.	40–90 ft-lb @ 6280 rpm	Static torque to determine failure load	10 test samples (5 samples each full and C-ring)

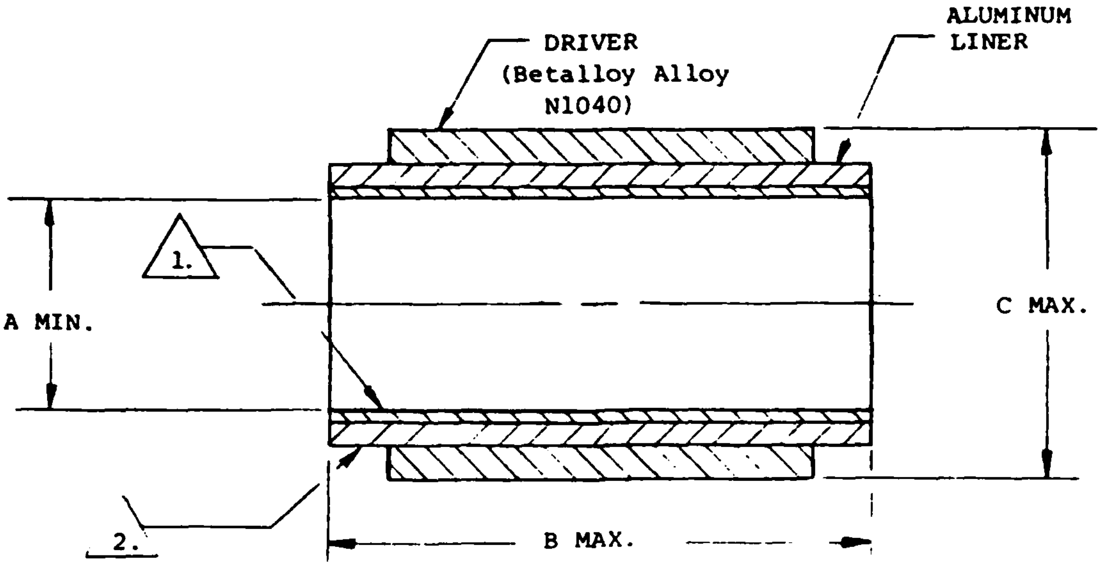
Table 3. TUBE MATERIAL CHARACTERISTICS

ITEM	NOMINAL SIZE (in.)	TUBING MATERIAL	OUTSIDE* DIAMETER (in.)	WALL* THICKNESS (in.)	COMMENTS	APPLICABLE SPEC (IF ANY)
Rigid Fluid Coupling	1/4	304 Stainless	0.250 +0.004 -0.000	0.030	--	MIL-T-6845C
	3/4	6061-T6 Aluminum	0.750	0.035	--	FED. SPEC. WW-T-700E/Gen
Flexible Fluid Coupling	3/16	Steel Reinforced TFE	0.312 +0.031 -0.008	0.040 +0.007 -0.005	--	MIL-H-27267A
	1/2	Steel Reinforced TFE	0.656 +0.031 -0.015	0.047 +0.007 -0.005	--	MIL-H-27267A
Control Tube Coupling	3/4	2024 Aluminum	0.750	0.028-0.037	Painted	WW-T-700/3E
	1-3/8	2024 Aluminum	1.375	0.035	Painted	WW-T-700/3E
Drive Shaft	1	2024 Aluminum	1.000	0.049	--	WW-T-700/3E

* Tolerances, where given, are from specifications. Other dimensions were taken from measurements of actual samples.

Table 4. PART DESCRIPTIONS AND NUMBERS

Item	Size (Inch, Dia)	Part No.	Page
Rigid Fluid Coupling	1/4	930105-.250	19
	3/4	930105-.750	19
Control Tube Coupling	3/4	930105-.750	19
	1-3/8	930105-1.375	19
Control Tube Coupling, C-Type	3/4	930110-.750	20
	1-3/8	930110-1.375	20
Flexible Tube Coupling	3/16	930108-.188	21
	1/2	930108-.500	21
Tail Rotor Drive, C-Type	3/4	930113-.750	22
	3	930113-3.000	22
Interlocking-C	3/4	930379	23
Heater Module	1/4	910862	24
	3/4	910861	25



TUBE SIZE	PART NO.	A MIN.	B MAX.	C MAX.
.250 +.005 -.000	930105-.250	.256	.640	.572
.750 +.008 -.006	930105-.750	.759	1.845	1.122
1.000 +.009 -.006	930105-1.000	1.010	2.440	1.390
1.375 ±.010	930105-1.375	1.386	3.386	1.892

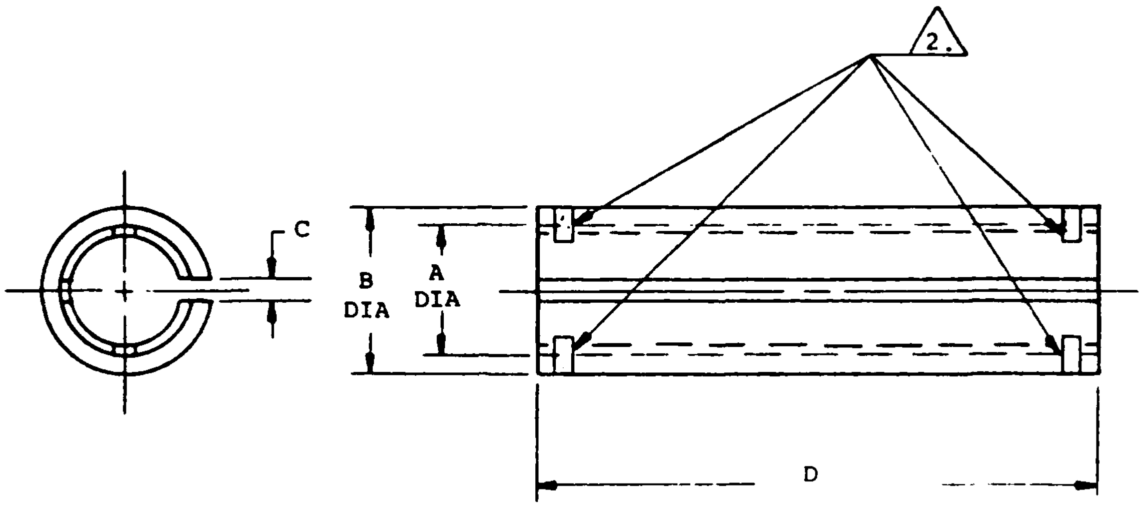
<u>NOTE</u>:

1. The I.D. of the liner is coated with heat curable epoxy.

2. The exposed O.D.'s of the liner are coated with thermochromic paint which changes color when the appropriate installation temperature is reached.

3. These couplings are intended for connecting hydraulic tubing of the dimensions shown in the table.

Figure 3. Outline drawing, rigid tube coupling.



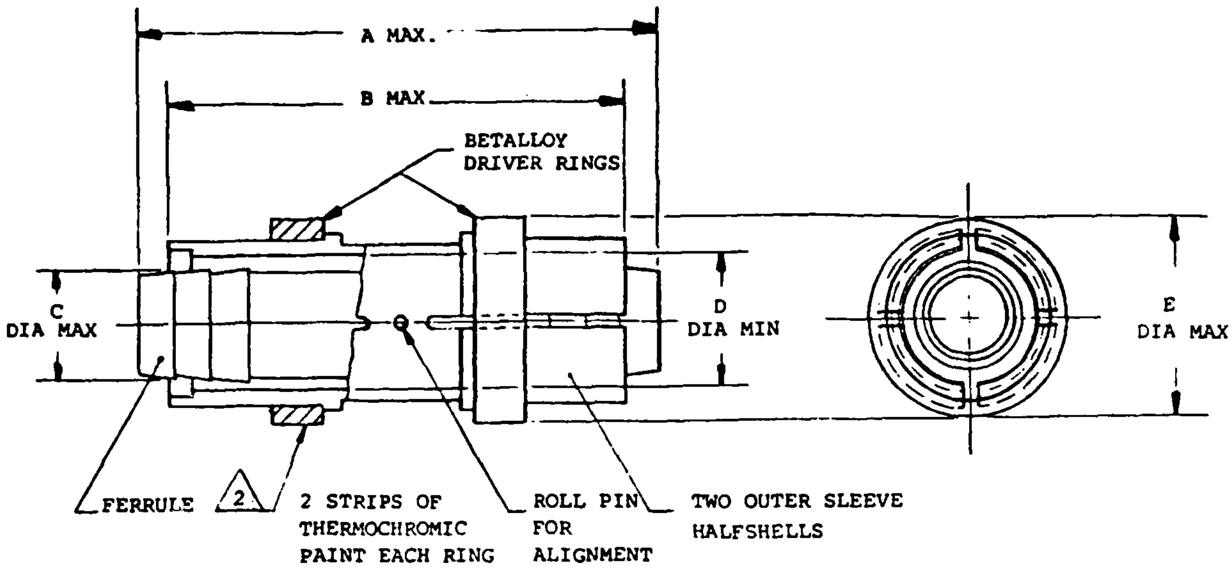
PART NUMBER	A MAX	B MAX	C MAX	D MAX
930110-.750	1.075	1.275	.800	3.250
930110-1.375	1.750	2.060	1.500	4.500

NOTE:

1. THIS COUPLING IS INTENDED FOR REPAIR OF DAMAGED CONTROL TUBES.

2. THE C-COUPLING IS MADE OF RAYCHEMS SHAPE MEMORY ALLOY, BETALLOY N1040 AND WILL SHRINK WHEN HEATED SUFFICIENTLY TO CHANGE THE THERMOCHROMIC PAINT FROM BLUE TO BLACK.

Figure 4. Outline drawing, "C" control tube coupling.



PART NUMBER	A MAX	B MAX	C DIA MAX	D DIA MIN	E DIA MAX
930108-.188	.980	.875	.211	.343	.545
930108-.500	2.585	2.285	.524	.687	1.165

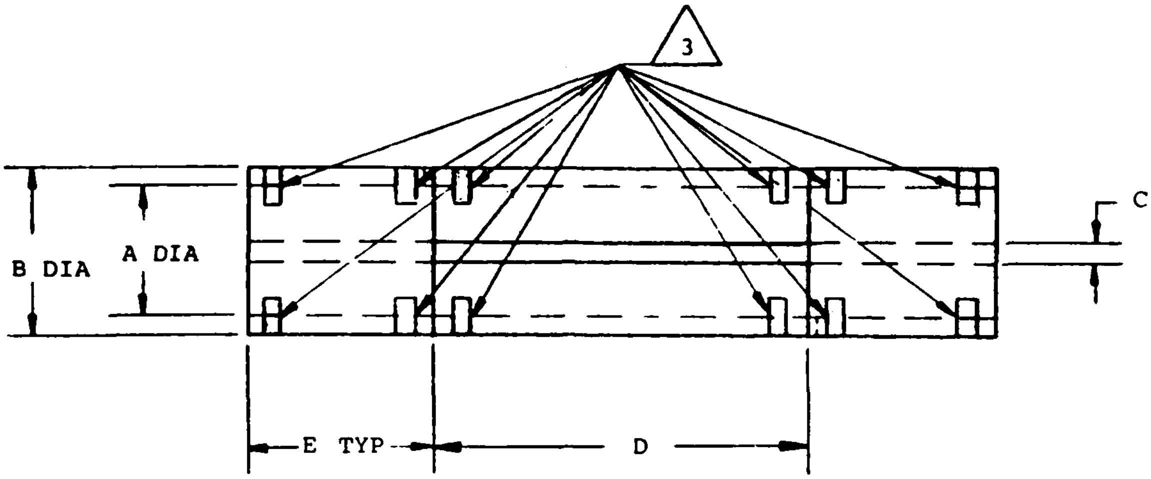
NOTE:

1. This coupling is intended for joining medium pressure high temperature braid-reinforced tetrafluoroethylene hose per Mil-Spec MIL-H-27267A.

2. The rings are made of Raychems shape memory alloy, Betalloy N1040 and will shrink when heated sufficiently to change the thermochromic paint from blue to black. The sleeve and ferrule are made of 303 stainless steel.

3. To assemble, slip one ring over each tube, insert the ferrule into each tube, push the halfshells together over the braid and onto the roll pins, slip the rings over the halfshells to the stops and shrink the rings without heating thermochromic paint directly.

Figure 5. Outline drawing, flexible tube coupling.



	Part Number	A MAX	B MAX	C MAX	D MAX	E MAX
2	930113- .750	1.075	1.275	.800	2.250	1.125
	930113-3.000	4.300	5.100	3.200	9.000	4.500

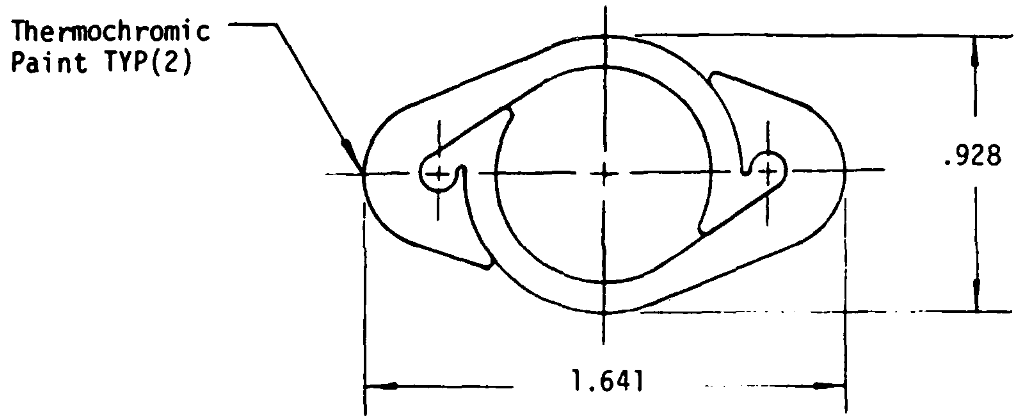
NOTE:

1. This coupling assembly is intended for repair of damaged tail rotor drive shafts.

2. This coupling is the 3/4 scale model for testing purposes only.

3. The C-couplings are made of Raychem's shape memory alloy, Betalloy N1040, and will shrink when heated sufficiently to change the thermochromic paint from blue to black.

Figure 6. Outline drawing, "C" tail rotor drive shaft coupling.



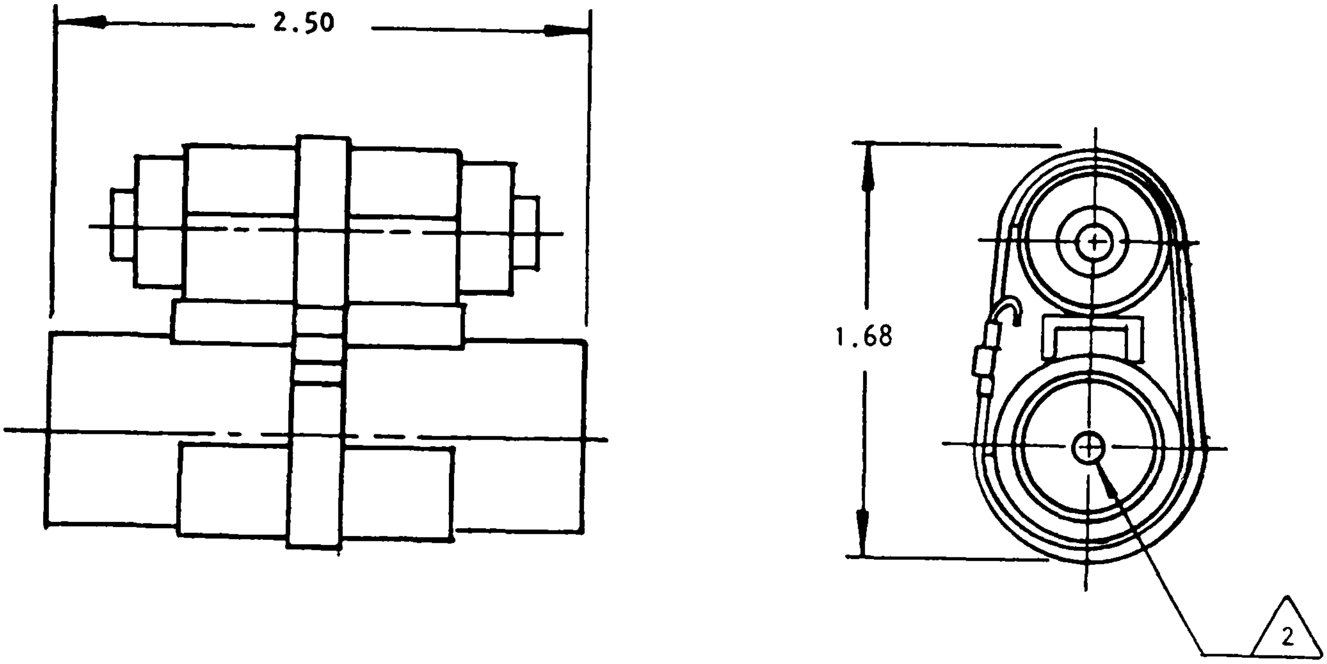
NOTES:

1. This product is intended to mechanically connect .750 2023 T3 aluminum tubing.

2. Each assembly is comprised of 2 identical components which interlock as shown. Each component is made of Betalloy, a heat shrinkable shape memory alloy made by Raychem.

3. Before installation, the coupling must be stored at temperatures below 50°C (125°F).

Figure 7. Outline drawing, interlocking coupling.



NOTE

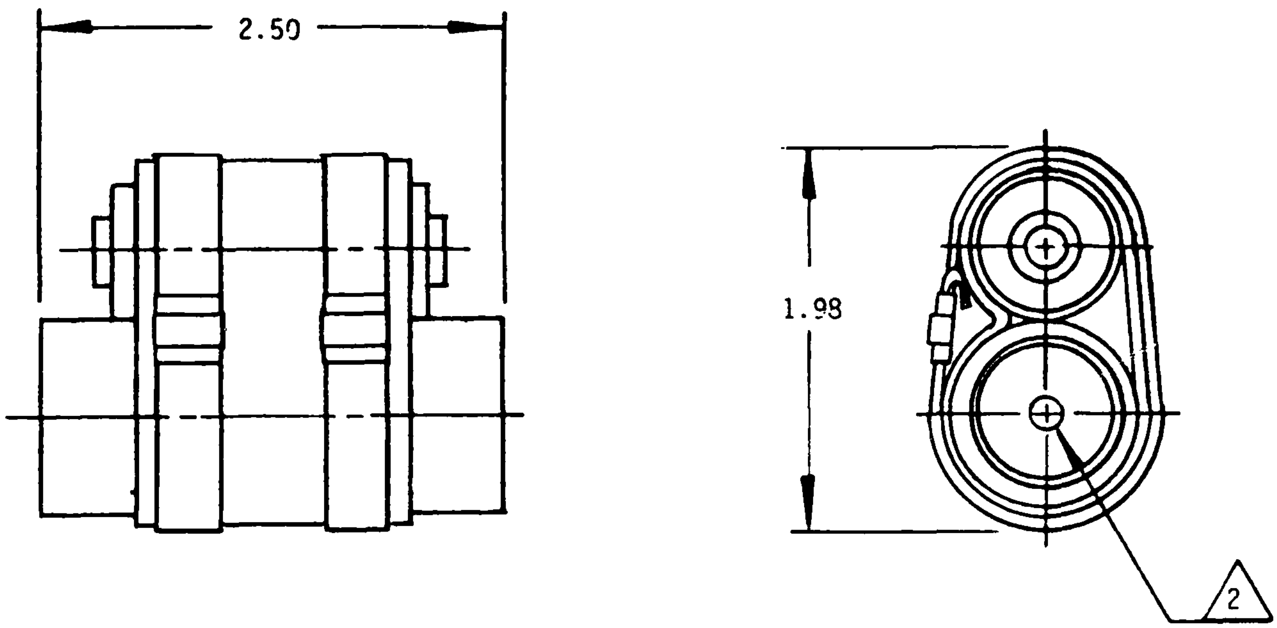
1. This heater is intended to be used with Raychem's heat shrinkable coupling per 930192-04.

2. This cartridge is a chemical heater which is activated by rapping a pointed instrument (punch or equivalent) with a blunt instrument (hammer or equivalent) at the location indicated. When the thermochromic paint on the coupling changes color installation is complete, but the heater should be allowed to cool before removing it.

3. The heater should be carefully stored in such a manner that it cannot be accidentally activated. Care should also be exercised during installation to avoid contact with the heater during the reaction.

4. Storage must always be maintained at a temperature less than 50°C.

Figure 8. Outline drawing, 1/4-inch heater module.



NOTE:

1. This coupling is intended to be used with Raychem's heat shrinkable coupling per 930192-12.

2. This cartridge is a chemical heater which is activated by rapping a pointed instrument (punch or equivalent) with a blunt instrument (hammer or equivalent) at the location indicated. When the thermochromic paint on the coupling changes color installation is complete, but the heater should be allowed to cool before removing it.

3. The heater should be carefully stored in such a manner that it cannot be accidentally activated. Care should also be exercised during installation to avoid contact with the heater during the reaction.

4. Storage must always be maintained at a temperature less than 50°C.

Figure 9. Outline drawing, 3/4-inch heater module.

TESTING

This section describes the detailed testing performed on each part. Several parts required more than one design iteration. In these cases, test data for both designs is described. In those cases where test results were not totally satisfactory, reasons for inadequate performance are given along with suggestions for improvements.

Impulse testing was done by APT Laboratories in Buena Park, California, under the direction of Mr. Barney Alstad. Compression Testing (column loads) was done by Hales Testing Laboratories in Oakland, California.

1/4-Inch Rigid Fluid Line Coupling

Table 5 shows test results for this coupling. The gas hydraulic tests were performed early in the program. Impulse testing was done on additional samples as a lot near the end of the program. There were no failures below the desired performance level. This item is considered qualified for its intended use with rigid fluid line repairs.

3/4-Inch Rigid Fluid Line Coupling

Table 6 tabulates the test data for this component. Additional data over that performed during phase I includes five samples which were hydraulically impulse tested. These latter tests were conducted without a reported failure to the 200,000 cycle limit. The testing of this product has been without incident, and this coupling is considered qualified for its intended use.

3/4-Inch Control Tube Coupling (Full-Ring Design)

A total of 49 sample couplings were tested during the program to illustrate the performance of the coupling under a variety of installation and environmental conditions. A summary of the data is shown in Table 7. Figures 13 through 16 show much of this data in graphical form to illustrate trends

in performance. The first three samples were done with actual painted control tubes. The test data indicated that paint should be removed for proper operation, so the remaining samples used equal-quality tubing without paint.

It was discovered at an early point that the tensile force was limited by the strength of the coupling liner. Tests were therefore done to determine the difference in tensile performance with both annealed and unannealed liners. This data is presented in Figure 10 as a function of the gap between tube ends. It is clear that unannealed liners offer substantial improvement in tensile performance over annealed ones. Also, tensile performance is not dramatically degraded if couplings are installed with gaps between the tube ends up to 100 percent of the tube diameter.

Data was collected to determine the sustained performance of the couplings when exposed to hot temperatures for long periods of time. Samples 15 through 24 shown in Figure 11 were tensile tested after being exposed to 400°F for periods of time up to and including 150 hours. These parts were with unannealed liners. The data shows an initial reduction in tensile strength in the first 50 to 75 hours, followed by level performance at 90 percent of the original. There is no detectable difference due to gap spacings of 0.15 and 0.30 inch, as expected from a consideration of Figure 10. Figure 12 shows similar data for samples 25 through 39 with annealed liners.

Because control tubes are used in both compression and tension modes, samples 40 through 49 were tested to understand performance under these conditions. Figure 13 presents this data. Both compression and tension tests were done on a common coupling, compression being done first. The failure mode during the compression portion of the test was defined as a "column bending" of the aluminum tubing. The couplings did not fail. Tensile performance after the compression failure was typical and the failure mode was defined as the usual tubing pulled from the coupling. Figure 13 indicates that although the performance degrades with increasing gaps between tube ends, the components are still useful up to gap lengths of 100 percent of the tubing diameter.

Table 5. 1/4-INCH RIGID FLUID LINE COUPLING TEST DATA

GAS/HYDRAULIC TESTS			HYDRAULIC TEST	
SAMPLE NUMBER	GAS TEST 700 PSI/ 5 MINUTES	PROOF 6000 PSI/ 5 MINUTES	BURST (PSI)	NOTE
1	No leak	No leak	15,000	1,3
2	No leak	No leak	10,000	1,3
3	No leak	--	9,000	1,2
4	No leak	No leak	11,000	1,3
5	No leak	No leak	9,750	1,3

IMPULSE TESTS

SAMPLE NUMBER	PEAK PRESSURE (PSI)	CYCLES	RESULTS
6-10	4500	200,000	No failures

Notes:

1. Tube ends were abraded with No. 150 emery paper prior to assembly.
2. A surge in the pressure pump expelled one tube during proof testing at 9,000 psi.
3. Tube expelled from coupling.

Table 6. 3/4-INCH RIGID FLUID LINE COUPLING TEST DATA

GAS/HYDRAULIC TESTS

SAMPLE NUMBER	GAS TEST 700 PSI/ 5 MINUTES	HYDRAULIC TEST 1500 PSI/ 5 MINUTES	HYDRAULIC TEST BURST (PSI)	NOTE
1	No leak	No leak	6,250	1,3
2	No leak	No leak	6,250	1,2,3
3	No leak	No leak	6,500	1,2,3

IMPULSE TESTS

SAMPLE NUMBER	PEAK PRESSURE (PSI)	CYCLES	RESULTS
4-8	2250	200,000	No failures

Notes:

1. Tube ends were abraded with No. 150 emery paper prior to assembly.
2. These samples were hydraulically proof-tested at 2000 psi for 5 minutes instead of 1500 psi for 5 minutes.
3. Tube burst.

Table 7. 3/4-INCH CONTROL TUBE COUPLING (FULL-RING DESIGN) TEST DATA

SAMPLE NUMBER	TENSILE FORCE (lb)	TEST CONDITION	NOTES FIGURES
1	1480	None	Note 1, 2, 3
2	2000	Surface abraded; bare aluminum in places.	Note 1, 2, 3
3	2750	All paint removed.	Note 1, 2, 4
4-9	2500-2665	Different gap spacing. Annealed lines.	Figure 3, Note 1, 2, 4
10-14	3730-4325	Different gap spacing. Unannealed liner.	Figure 3, Note 1, 2, 5
15-19	3975-4500	400°F for 150 hr. 0.150 gap.	Figure 4, Note 1, 2
20-24	3880-4370	400°F for 150 hr. 0.300 gap.	igure 4, Note 1, 2
25-39	2450-2750	400°F for 150 hr. Annealed liner.	Figure 5, Note 1, 2
40-49	2420-3530	Compressive load. Variable gap.	Figure 6, Note 1, 2, 6
	4000-4840	Tensile load. Variable gap.	Figure 6 Note 1, 2

Notes:

1. Actual control tubes used for samples 1-3. Remaining tests used similar but unpainted tubing.
2. Abrasion of tube ends done with No. 150 emery paper.
3. Failure mode was a pulled-out tube. Paint on the control tube adhered to coupling, not tube.
4. Failure mode was a splitting of the coupling liner in the center.
5. Tubing pulled out of coupling.
6. Failure was column bending of tubing. Tensile test performed after compression on same sample.

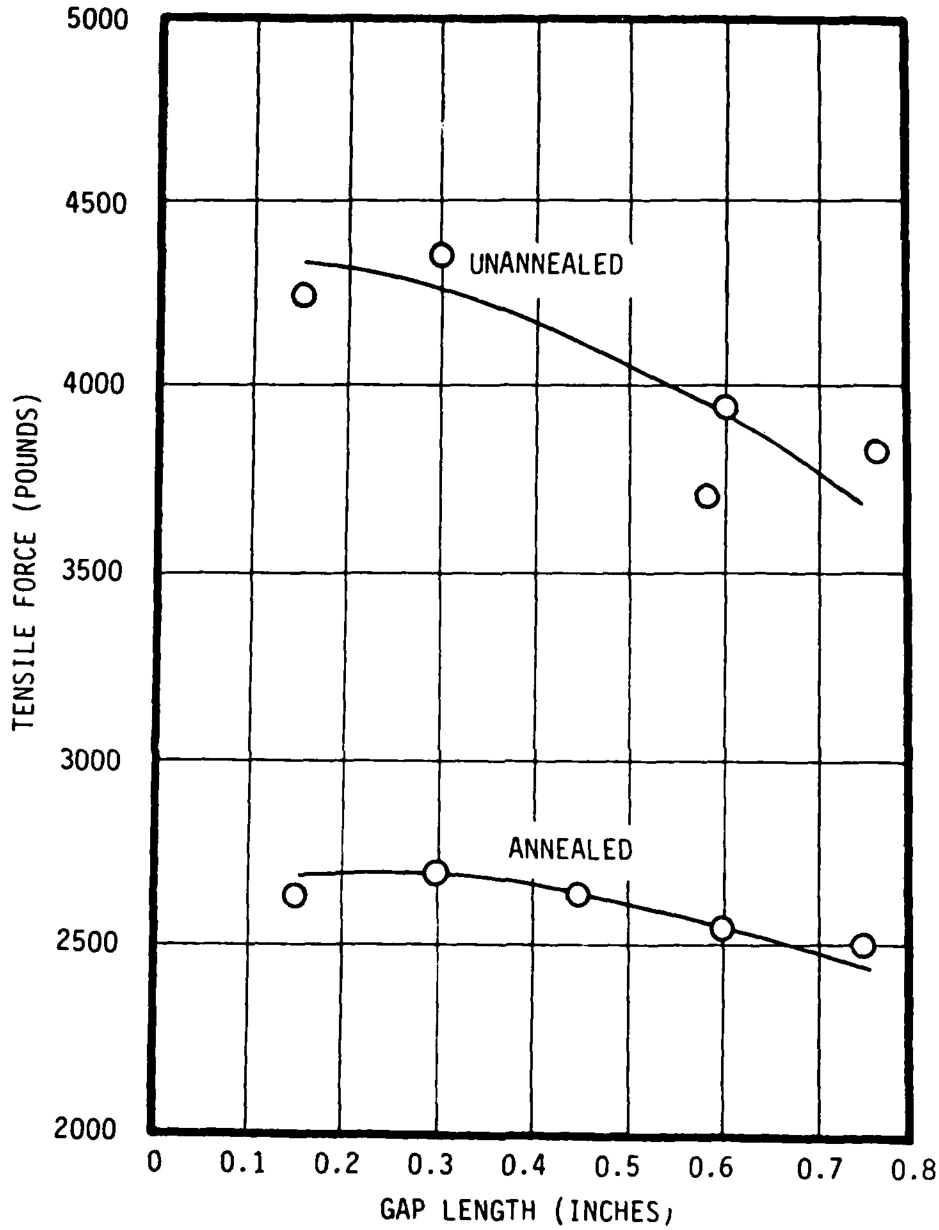


Figure 10. Tensile force for 3/4-inch couplings versus end gap spacing.

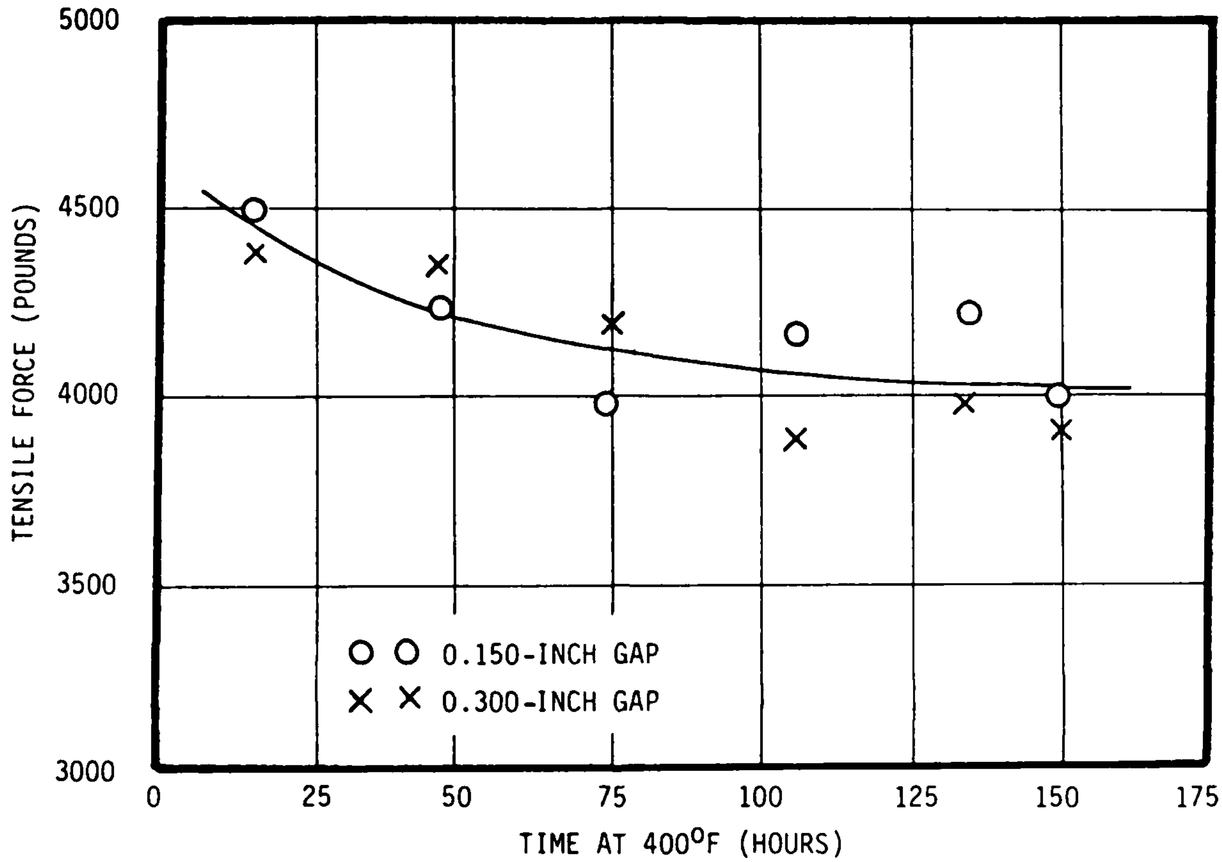


Figure 11. Tensile force for 3/4-inch control tube couplings versus tempature soak, unannealed liners.

The conclusion from the voluminous data taken with the 3/4-inch control tube coupling is that the design either meets or exceeds all the performance criteria. It is considered qualified for the intended use.

1-3/8-Inch Control Tube Coupling (Full-Ring Design)

Table 8 tabulates the data taken on two designs using annealed and unannealed liners. During the first part of the program, the tested couplings failed with split liners under tensile stresses, as the data shows. During the second phase of the program, the part was modified to use unannealed liners and the tensile performance improved by 50 percent. Table 8 also shows that both compressive and tensile measurements were made on common couplings. In this case, however, the compressive force was not raised above 4500 pounds (the performance specification is 4000 pounds) to prevent damage to the tubing. Again the test data shows that tube end gaps up to 100 percent of the tube diameter do not seriously reduce performance. The part is considered qualified for the application intended.

3/4-Inch Control Tube Coupling (Split-Ring Design)

Table 9 summarizes the test on this product. Early experiments in phase I with the first six samples indicated that the addition of gripping items like teeth, silicon carbide grit, or other similar roughening techniques would enhance the properties of a smooth C-ring type coupling. A stainless steel liner with teeth was chosen for the design to be tested for phase II. Such an approach increases the tensile performance from nominally 500 pounds to over 800 pounds. The strength is limited by the contact area of the recovered part which only makes good contact with the tubing in three places (two ends and middle of the expanded C-ring). The part can be made stronger to overcome the lack of surface area, but only to the point of collapsing the tubing. Samples 2-6 of the second design indicate both the compressive and tensile performance as a function of end gap spacing. The low value at 0 gap (sample no. 2) is unexplained to date. The remainder of the data,

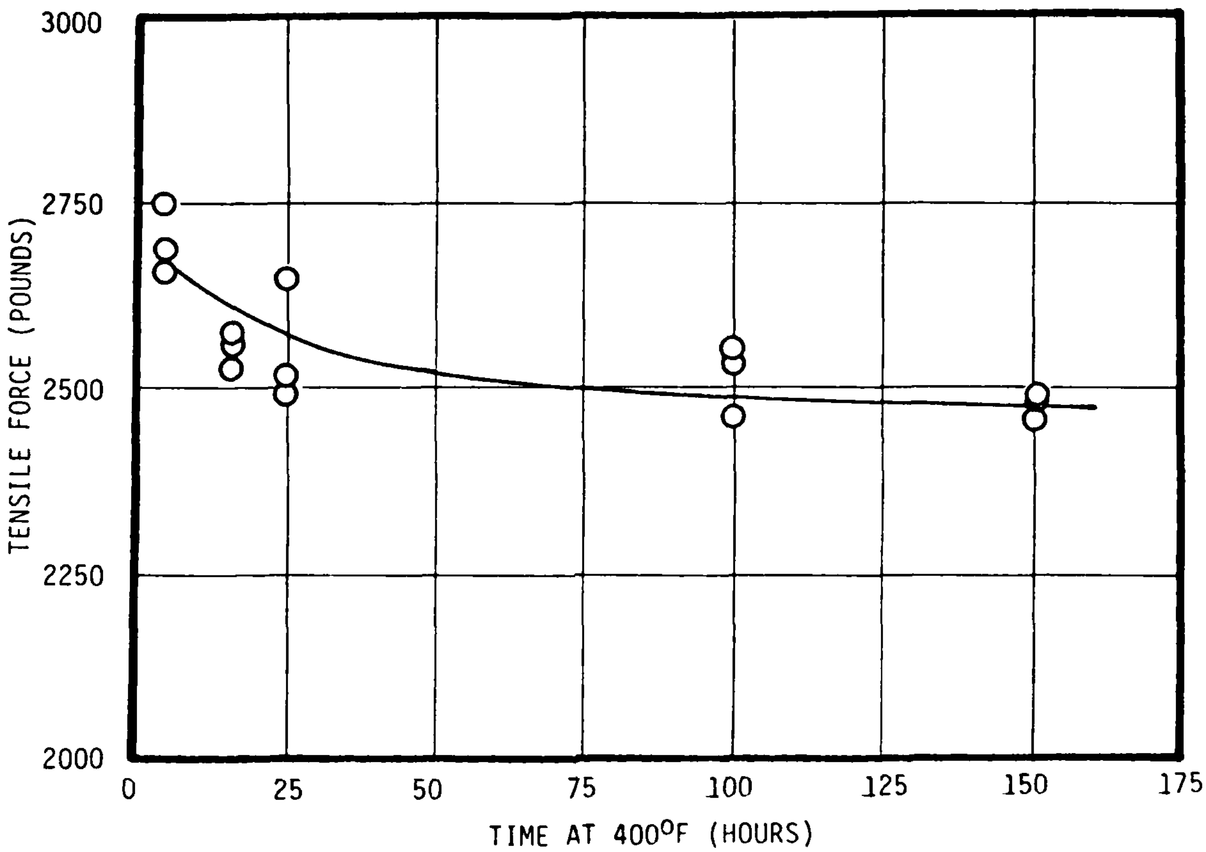


Figure 12. Tensile force for 3/4-inch control tube coupling versus temperature soak; annealed liners; minimum gap spacing.

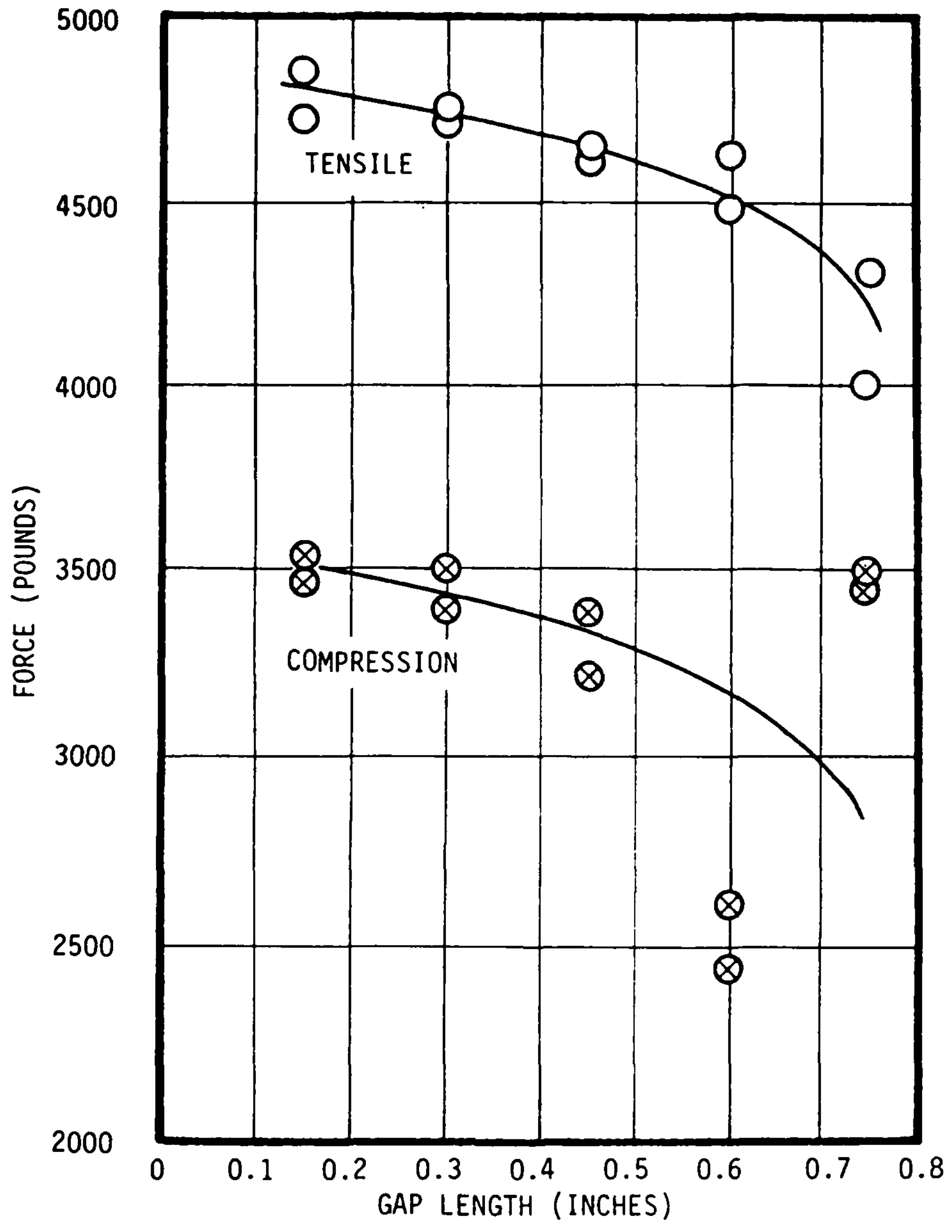


Figure 13. Compressive and tensile forces for 3/4-inch control tube coupling versus end gap spacing.

Table 8. 1-3/8-INCH CONTROL TUBE COUPLING (FULL-RING DESIGN) TEST DATA

DESIGN NO. 1 (ANNEALED LINER)

SAMPLE NUMBER	FORCES (lb) COMPRESSIVE	TENSILE	TEST CONDITIONS	NOTES
1	--	5600	Sanded tube	1
2	--	5290	Sanded tube	1
3	--	5150	Sanded tube	1
4	--	4940	Sanded tube	1
5	--	5250	Sanded tube	1

DESIGN NO. 2 (UNANNEALED LINER)

SAMPLE NUMBER	FORCES (lb) COMPRESSIVE	TENSILE	TEST CONDITIONS	NOTES
1	--	7500	0 gap	2, 4
2	4500	7860	0.550-inch gap	3, 4
3	4500	7810	0.825-inch gap	3, 4
4	4500	7930	1.110-inch gap	3, 4
5	4500	7300	1.375-inch gap	3, 4

Notes:

1. Failure mechanism was a splitting of the liner.
2. No compressive test made for zero gap.
3. No failure on compression; test terminated at 4500 pounds.
4. Tube pulled out on tensile failure.

although statistically more scattered than usual, shows that the end gap spacing has little effect on the compressive and tensile properties up to 200 percent of the tube diameter. Because the same sample was used for both compression and tensile tests, the observed tensile performance is lower than usual. The compression testing (done first) "broke the grip" of the part, allowing it to slide easier in the tensile mode.

Figure 14 shows the effect of adding a split-ring coupling to a damaged tube. In these tests, a calibrated slot of varying degree was supported with a coupling and the resulting performance measured. Figure 14 shows that 200-500 pounds additional strength can be added to the damaged tubing with the coupling. This is a value anticipated from the nominal performance with severed tubing. Figure 15 shows the effect of heat soaking 3/4-inch split-ring couplings. Although the data is scattered, a definite trend is observed showing that the tensile strength of the coupling drops to less than 50 percent of its original value after soaking 150 hours at 300°F. This data supports some earlier data which Raychem has taken on split-ring designs, indicating that the effect of thermal creep on some designs is prominent. The effect, of course, is less dramatic at lower temperatures. Other data indicates that there is little effect below about 200°F. It is clear that such items should have limited usage where hot temperature extremes are expected.

The benefit of the split-ring C-type coupling in battle damage repair is the potential usage on unsevered tubing. To assemble a split-ring on a piece of damaged tubing, the ring must be opened greater than the diameter of the tubing. To date this has not been accomplished in this program, although results have been very close. Over 90 percent of the diameter has been achieved, but a full diameter cannot be expanded without fracturing the part during expansion. It is believed that a dramatically different design with nonuniform cross sections and/or the choice of the different alloy would allow a part to be expanded greater than a tube diameter. Thinner sections can be used, but only at the expense of strength. Further designs and alloy investigations are believed to be beyond the current scope of the existing program. These facts, combined

Table 9. 3/4-INCH CONTROL TUBE COUPLING (SPLIT-RING DESIGN) TEST DATA

DESIGN NO. 1 (NO LINER)

SAMPLE NUMBER	FORCES (lb) COMPRESSIVE	TENSILE	TEST CONDITIONS	NOTES
1	--	380	Sanded tube	2,3
2	--	390	Sanded tube	1,2,3
3	--	410	Sanded tube	2,3
4	--	570	Sanded tube	4,3
5	--	600	Sanded tube	5,3
6	--	550	Sanded tube	5,3

DESIGN NO. 2 (WITH LINER)

SAMPLE NUMBER	FORCES (lb) COMPRESSIVE	TENSILE	TEST CONDITIONS	NOTES
1	--	850		3,6
2	--	180	0 gap	
3	390	200	0.6-inch gap	7
4	220	300	0.9-inch gap	7
5	160-230	150	1.2-inch gap	7,8
6	330-500	320	1.5-inch gap	7,8
7-16	--	2030-3600	Calibrated damage	Figure 8
17-26	--	172-460	Heat soak at 400°F	Figure 9

Notes:

1. 0.29-inch wall thickness. Other tubing 0.035-0.037 inch.
2. Loctite™ with no. 80 silicone carbide added to tube ends prior to installation.
3. Cryogenically installed and heated.
4. Toothed liner included without silicone carbide.
5. Thicker part without silicone carbide.
6. Tube surface sanded.
7. Compressive force applied first until slippage, then tensile force applied.
8. Part started to slip at lower value but sustained higher value during slippage.

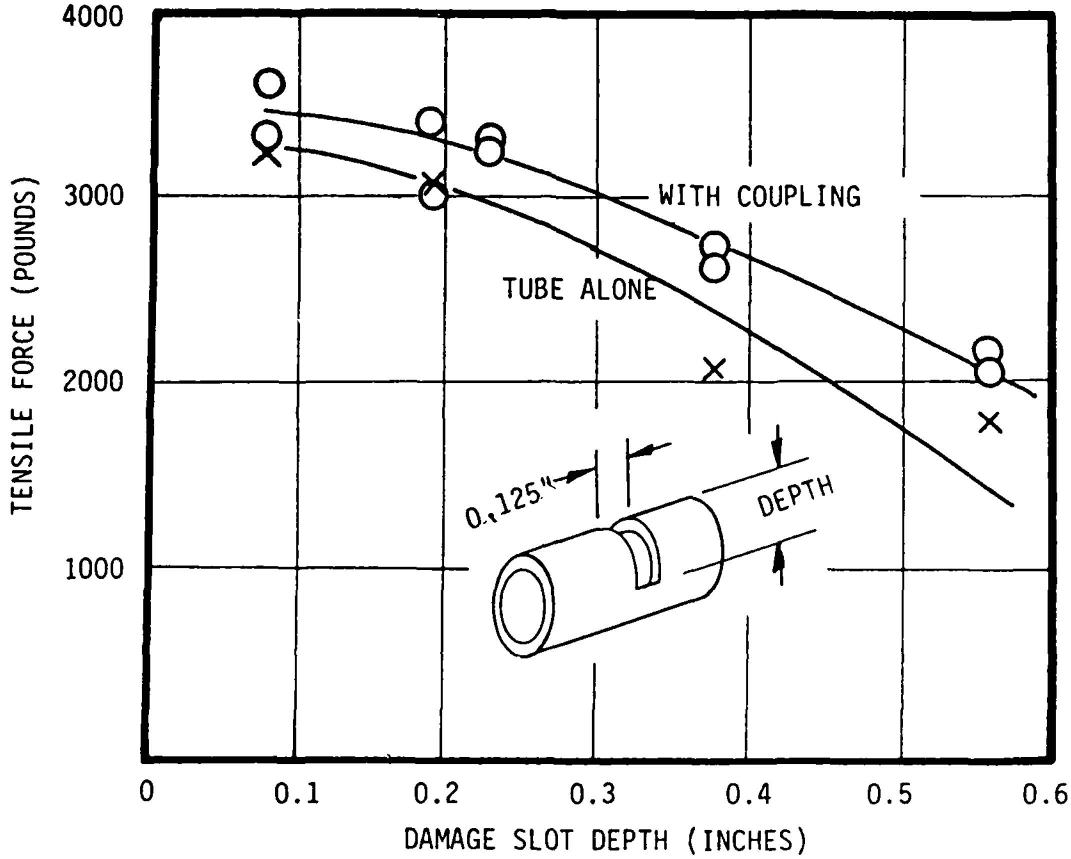


Figure 14. Tensile performance of 3/4-inch control tube coupling (split-ring design) versus tubing damage.

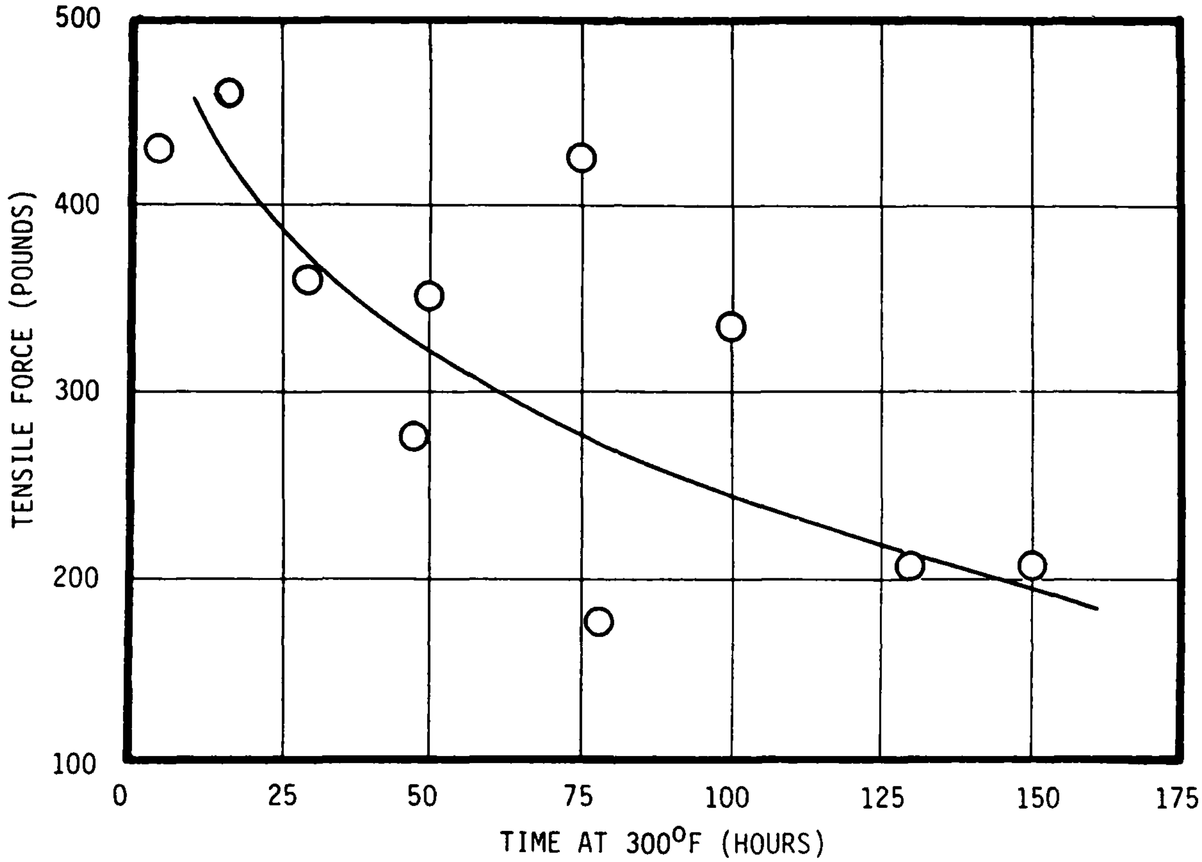


Figure 15. Tensile performance of a 3/4-inch split-ring coupling versus time soaked at 300°F.

with the loss of strength with extended heat soak, lead to the conclusion that the split-ring coupling in its present configuration is not suitable for practical battle damage repair scenarios.

1-3/8-Inch Control Tube Coupling (Split-Ring Design)

Table 10 shows the data accumulated for this design. It is a similar design to the 3/4-inch size with similar results. It also has a common problem of not expanding more than full tube diameter. This part is also unsuitable for practical repair without additional design/engineering efforts being applied.

1-Inch Drive Shaft

Table 11 shows torque data measured on this coupling. The values were measured with a torque wrench (175 ft-lb maximum limit) until slippage was detected. Samples 4 and 5 had significantly lower torque limits than the previous three samples. The two samples were inspected and determined to have an insufficient coating of epoxy on the inside liner. Since the epoxy is a carrier for a quartz "grit," it is believed that the low values are the result of inadequate abrasive. Even the values of 4 and 5, however, meet or exceed the performance requirements. It is concluded, therefore, that the 1-inch drive shaft is qualified and suitable for usage.

1/2-Inch Flexible Fluid Coupling

Table 12 lists data taken on this coupling. Tests on design no. 1 in phase I of the program were generally unsuccessful with leaks and/or burst failures at hydraulic pressure less than 2000 psi. Failure analysis indicated that a disproportionate load was being put on the Teflon portion of the cable instead of the armor braid. The design was modified significantly to one which distributed the load and sealing

Table 10. 1-3/8-INCH CONTROL TUBE COUPLING (SPLIT-RING DESIGN) TEST DATA

SAMPLE	FORCES (lb)		TEST	
NUMBER	COMPRESSIVE	TENSILE	CONDITIONS	NOTES
1	--	820	Liner, driver gaps same side	1,2,3
2	--	1910	Liner, driver gaps opposite side	1,2
3	--	870	0 gap	
4	1260	1010	0.85-inch gap	4
5	930	750	1.29-inch gap	4
6	860	780	1.68-inch gap	4
7	710-1100	780	2.10-inch gap	4,5

Notes:

1. One tube sanded.

2. Cryogenically installed and heated.

3. Tube split on recovery. Failure (tube pulled out) on unsanded side.

4. Compressive force applied just until slippage, then tensile force applied.

5. Part started to slip at lower value but sustained higher value during slippage.

properties to the armor braid and Teflon, respectively. The first sample of this design did not leak gas at 600 psi and sustained a hydraulic fluid pressure of 4500 psi before bursting. With this success, five additional samples were prepared for formal impulse testing. All passed the gas test at 1000 psi but failed to pass the proof pressure testing prior to impulse testing. Failure analysis indicated that the flexible tube used for the impulse test samples had different size and configuration armor braid than that used in prior test articles. Even though ordered to the military specification, the tolerances on the braid and its pattern are such that the design coupling would not sustain pressure. There is sufficient test evidence to support the conclusion that a coupling could be made which would pass performance requirements for a very specific flexible tubing. However, it is believed that a different part with dimensions adjusted to each type of braid would be required.

The 4-percent maximum recovery capabilities of Betalloy are not sufficient to accommodate the loose tolerances of the tubing for a practical field repair device. Inventory of many parts would be necessary to accommodate the wide range of tolerances. No further parts were built or tested due to this ambiguity. It is concluded that although possible, the design of such a coupling is impractical without more stringent control of the dimensional parameters of the tubing.

3/16-Inch Flexible Fluid Coupling

Table 13 lists data for this coupling. The results are very similar to those for the 1/2-inch coupling. The part had random gas leaks, although no hydraulic leaks, and sustained a burst pressure at approximately the proof test pressure. The conclusion is the same as for the 1/2-inch coupling. One final point is useful. Assembly of couplings to flexible hydraulic hose is quite craft-sensitive. This is true even for existing compression-type fittings, although it is expected to be more stringent for the proposed shape-memory couplings. To facilitate a reliable connection, it is anticipated that a set of special tools for cutting and preparing the ends of the tubing would be required.

Table 11. 1-INCH DRIVE SHAFT TEST DATA

SAMPLE NUMBER	TORQUE (ft-lb)	NOTES
1	165	2
2	175	3
3	175	3
4	65	4
5	40	4

Notes:

1. Tube material is 2024-T3 aluminum.
2. Tube end broke.
3. 175 ft-lb is limit of torque wrench.
4. Epoxy coating thin.

Table 12. 1/2-INCH FLEXIBLE FLUID COUPLING TEST DATA

DESIGN NO. 1

SAMPLE NUMBER	HYDRAULIC TEST	NOTES
1	Leak @ 1500 psi	1,4
2	Leak @ 1800 psi	1,4
3a	Expelled tube at 1000 psi	1,4
3b	Leak @ 1300 psi	1,2,4
4	Leak @ 1500 psi	1,3,4
5	Leak @ 1750 psi	1,3,5
6	Leak @ 1300 psi	1,3,5

DESIGN NO. 2 (3-RING STYLE)

SAMPLE NUMBER	GAS TEST	HYDRAULIC TEST	NOTES
1	No leak @ 600 psi	4500 burst	
2	No leak @ 1000 psi	1200 burst	
3	No leak @ 1000 psi	1750 burst	
4	No leak @ 1000 psi	1600 burst	7
5	No leak @ 1000 psi	1950 burst	6
6	No leak @ 1000 psi	2000 burst	6,7

Notes:

1. Rings were assembled cryogenically on all design no. 1 parts.
2. Sample 3a was installed and tested; tubing was reinserted and retested with new ring on failed end for sample 3b.
3. Larger inner ferrule, split lever arm design.
4. Coupling was tested with pressurized water.
5. Coupling was tested with hydraulic fluid.
6. Passed 1875 psi proof prior to impulse test.
7. Slow leak at low N_2 pressure, none at 1000 psi.

3/4-Inch Interlocking Coupling

The inability to expand a "C" coupling greater than a tube diameter without fracture still left a need for couplings that could be used to reinforce damaged but unsevered tubing. Alternative approaches using half-shell type devices were considered. Bolts, rivets and strap techniques did not appear to have sufficient strength, theoretically, so an interlocking pair of identical half-shells as shown in Figure 8 was conceived and fabricated. This turned out to be a much more difficult part to fabricate than expected. Multiple extrusion die attempts were required before a successful length of material was extruded. Expansion of the part was similarly difficult. There is an extraordinary amount of "spring-back" in the expansion which has to date made preconditioned parts difficult to fabricate. The data shown in Table 14 was necessarily done with nonconditioned parts (assembled cryogenically). Preconditioned parts have been made, but the yield is low and the clearance during assembly is small. Nevertheless, the part performs quite well, as indicated by the data of Table 14.

Flameless Heaters

The catalytic flameless heater developed in phase I proved adequate but overdesigned and costly to manufacture. The parts have been redesigned for manufacturing economy and tested on both 1/4- and 3/4-inch couplings successfully. The heaters have been designed to be an integral part of the coupling during the manufacturing process. They are easily removed after the heater is used, although they are not capable of field installation onto a coupling. This eliminates the need to inventory separate coupling and heaters and saves installation time in the field. This catalytic heater approach eliminates the need for an open flame. However, the heating element does get hot (about 800°C) and requires precautions in handling and installation. The heat cartridges themselves are adapted from a product made by Metrotell Corporation for usage with field soldering tools. They are available only in one size although they can be scaled to other sizes--a desirable approach if production quantities of small size couplings are required. To date, Metrotell is the only known vendor of these cartridges.

Table 13. 3/16-INCH FLEXIBLE FLUID COUPLING TEST DATA

SAMPLE NUMBER	GAS TEST	HYDRAULIC TEST	NOTES
1	No leak @ 700 psi	3000 psi burst	
2	No leak @ 1000 psi	2250 psi burst	
3	No leak @ 1000 psi	2400 psi burst	
4	Leaked	2800 psi burst	1,2
5	No leak @ 1000 psi	2400 psi burst	
6	Leaked	2600 psi burst	1,2

Notes:

1. Exact pressure not recorded.
2. Passed 2500 psi proof prior to burst test.

Table 14. 3/4-INCH INTERLOCKING COUPLING TEST DATA

SAMPLE NUMBER	ULTIMATE TENSILE STRENGTH (lbs)	NOTES
1	2420	1,2
2	2530	1,2
3	2770	1,2
4	1720	1,2,3

SAMPLE NUMBER	ULTIMATE TORQUE RESISTANCE (ft-lbs)	NOTES
5	70	1,2
6	72	1,2
7	76	1,2,4
8	67	1,2

Notes:

1. Test tubing was 2024-T3 aluminum, 0.75 OD, 0.030 wall.
2. Parts assembled cryogenically and heated.
3. This coupling was cracked before assembly.
4. Tubing broke at 76 ft-lb.

CONCLUSIONS

The amount of successful data accumulated during this program leaves little doubt that shape memory metal can play an important role in battlefield repair of damaged helicopters. The strength of the material can often repair tubing to near-new performance. The full-ring coupling is a valid repair tool in its present configuration. Testing to date has shown it to be both efficient in use and high in performance. Usage on flightworthy aircraft, however, should not be permitted until an exhaustive qualification program has been successfully completed. Split-ring couplings, interlocking couplings and flexible couplings have been shown to be possible with shape memory brass but not sufficiently mature in design to recommend near-term usage on flightworthy aircraft. In all these latter cases, the limited memory of shape-memory brass (typically 3-4 percent) made parts somewhat skill sensitive in installation. It is anticipated that much of this sensitivity could be eliminated with extra design effort. Also, other alloys such as Tinel with 8 percent memory used in conjunction with suitable crimp designs would eliminate these problems.

RECOMMENDATIONS

It is recommended that flameless electric heaters be considered as alternatives to the catalytic type. Finally, the applicability of shape memory metals to battle-damage repair of non-tubing items should not be ignored. The lightweight, compact and strong nature of shape-memory metal makes it a natural tool for battle-damage repair. Clamps, bolts, rivets, shrinking wire and strip could all play an important part in future battle-damage repair.

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